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MACHINING OF OPTICS: AN INTRODUCTION

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Major, USAF

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Final Report

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AIR FORCE WEAPONS LABORATORY

Air Force Systems Command

Kirtland Air Force Base, NM 87117

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This technical report has been reviewed and is approved for publication.

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Machining of optics: an introduction

Theodore T. Saito

This paper introduces machining of optics, presenting some of the history of machining progress, critical machining variables, material and geometrical capabilities, and some new results on optical evaluation of machined surfaces. A most significant development is electroplating of materials that are otherwise not presently machinable. For example, molybdenum has been electroplated with silver or gold and then successfully diamond turned. Research and development ideas for future machining studies will be briefly discussed.

Introduction

The Machining of Optics Workshop was held in May 1974 in Boulder, Colorado to present recent developments in techniques, materials, metrology, finishing, and use of machined optics. Two primary machining techniques were discussed: single-point diamond turning and techniques that include precision grinding and polishing. This paper presents some of the history of machining progress, critical machining variables, material and geometrical capabilities, and some new results on optical evaluation of machined surfaces. Research and development ideas for future machining studies are briefly discussed.

Diamond turning of optics can be defined as the use of a diamond tool on a precision lathe under very precisely controlled machine and environmental conditions to fabricate a finished optical component.[1-3] The technique has also been referred to as micromachining and precision surface generation (PSG).

Diamond turning is not a new technique. As this author spends more time investigating machining of optics, he finds reports of earlier work. The earliest work presently known to this author is by Frank Cooke of Cooke Optical (N. Brookfield, Massachusetts) during World War II. Much early research was done also by Phillips Electric (Endhoven, Holland); duPont (Wilmington, Delaware); Perkin Elmer (Norwalk, Connecticut); and Bryant-Symons (London, England).[4-6] In early 1963, developmental emphasis was added in order to obtain better than 1-μm part accuracy. Much early research was performed by Y-12 (Union Carbide, Nuclear Division, plant operated for Atomic Energy Commission, A.E.C., Oak Ridge, Tennessee), Lawrence Livermore Laboratories (L.L.L.), and Battelle Pacific Northwest Laboratories. Los Alamos Scientific Laboratories was an important catalyst for applying machining technology to optics. A significant development for diamond turning was the air-bearing spindle.

In order to diamond turn high quality surfaces, it is necessary to pay careful attention to the following variables[5]:

(1) Diamond tool: Most work has been performed with single-crystal diamonds with a radius of curvature on the order of a few millimeters. Multicrystal diamonds have been used for glass work. The tools are carefully lapped with a 0.25-μm diamond abrasive to finish the edge.

Tools are inspected under magnifications (400× is common) to ensure that the cutting edge is free from defects. Defects in the tool result in a rainbow effect, i.e., diffraction of reflected light resembling the rainbow. Silver samples with the rainbow effect had several tenths of a percent increased 10.6-μm absorption as compared to rainbow free samples fabricated in an otherwise similar manner. Tool sharpness is important for high quality. Chips of 750-Å thickness indicate that a sharpness of 250 Å is common.

(2) Precise machine movements must be maintained so that the wander of the tool or the piece during machining does not cause surface irregularities.

(3) Lack of vibration of the spindle and tool is obtained by careful selection of the belts used to couple the motor to the shafts and by vibration isolation mounts.

(4) Dynamic balancing by sophisticated electronic techniques has helped reduce cyclic geometry errors. It is necessary to balance the piece at the rpm that it will be cut. Lack of balance will create problems similar to imprecise machine movements.

(5) Temperature control is obtained by controlling the temperature of the room to within ±1°F. The

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number of people in the room is also controlled so as to help maintain thermal stability. The cutting fluid and its application have an influence on the temperature of the tool and workpiece. Lawrence Livermore Laboratories employ an oil shower to stabilize thermally the complete machine.[6,7] Efforts have also been made to cool the spindle.

Diamond turning has been successfully performed on copper, gold, silver, aluminum, platinum, lead, nickel, irtran (ZnS), and plastic. Face-centered cubics have generally been successful. Molybdenum and steel have not been successfully machined yet. Electrostatic cooling of steel may offer a significant step forward in machining.

Electroplating offers significant material flexibility for machined optics, as well as providing high reflectivity surfaces. Y-12 recently electroplated gold and silver on molybdenum and then successfully diamond turned them. The details of the results are discussed in the paper by Arnold in this issue.[8] Any material that can be electroplated with silver, gold, or copper can be finished by diamond turning! One significant additional advantage of electroplating is related to refabrication of mirrors. Electroplating of about 10^{-2}-cm thickness can be applied so that refabrication of the optic only entails that a finishing cut be made on the machine, therefore reducing refabrication costs. Electroplating may also relieve noble metal coating requirements. Unfortunately, electroplating technology has many unanswered questions, especially those dealing with effects of trace (parts per million) additives to plating and optical quality. Waldrop's paper discusses technology and presents research in electroplating.[9]

Diamond turning has had the greatest success in generating flats. Optics of 1 m in diameter can presently be machined. Y-12 plans to modify a machine for 200-cm diam optics. Any object of revolution can be machined in principle, and computer software exists to input parameters for some closed form surface figures, such as spheres, parabolas, ellipses, and torroids. Y-12 has machined an aluminum parabola of approximately 1-m diam from which three 25-cm diam and three 5-cm diam off-axis parabolas were extracted. The blanks were inserted into the aluminum with rubber gel before the parabola was cut. The machined figure of the parabola over a 30-cm diam center section was within 14 μm of the true figure.[10]

An optical figure of diamond turned flats is 0.04 μm/cm in diameter. Optical figure for flat mirrors is often specified per diameter dimension because of nonstraightness of machining ways which are usually specified in μin./ft. The errors for a curved mirror are caused by several factors other than those already mentioned (i.e., tool geometry, setup, and slide feed errors). Therefore, one can only roughly estimate the figure error for generated surfaces 0.08 μm/cm in diameter.

It is important to note that shapes cut with one degree of freedom have a much better surface figure and surface finish than those cut with several degrees of freedom. An example of one degree of freedom tool movement is along a straight line or rotating about a fixed point. Geometries that can be cut with a single degree of freedom include flats, spheres, cylinders, axicons, and toroids.

The quality of diamond turned mirrors is outstanding for ir application. Nine brass samples, electroplated with silver and diamond turned by LLL, were measured by the 10.6-μm absorption calorimeter[11] at the Air Force Weapons Lab. The average and standard deviation of the nine samples without rainbow was 0.0071 ± 0.0002 indicating exceptionally low absorption with excellent absorption uniformity. Theoretical prediction of 10.6-μm absorption of silver is 0.0047, and the best reflectivity of silver UHV coated on metal substrates is 0.0062.[12-14] Table I summarizes the optical characterization of various diamond turned mirrors. The data for each entry were taken from the same mirror. Note how the total-integrated-scatter at 6328 Å (ITS) for brass/Ag is four times greater than Cu/Ag, but the brass/Ag has lower absorption. The difference in absorption may be due to the silver quality as the mirrors were electroplated by two different organizations.

In addition to specifying the over-all optical figure for machined surfaces, one should note the slope error. Figure 1 shows an interferometric flatness testing in reflection at 0.63 μm of a machined mirror. Although the deviation from flat is approximately ¼ of a fringe, it occurs in a very local area, i.e., the slope error is greater than a ¼ fringe error uniformly distributed over the whole mirror. This localized figure error in machined optics may be due to a bump in the way or an impulse disturbance to the machine structure. Minute distortion due to part support can also cause this type of error.

Besides the flexibility of producing optics with figures is difficult, if not impossible, to generate with conventional techniques, diamond turning of optics has the added advantage of reduced fabrication time. Starting with a metal blank machined to size, it takes about 1 day to finish with diamond turning, whereas, superpolishing takes several weeks.[16]

Table II summarizes the capabilities of organizations that have diamond turning capability. There are several techniques for generating nonflat surfaces. Y-12 has employed a technique where the length of the arm holding the diamond tool and the angle of the arm with respect to the axis of rotation are varied. Y-12's technique is called R-theta. LLL holds the length of the arm constant, varies the angle of the arm with respect to the axis of rotation, and changes the position of the arm along the axis. LLL's technique is called Z-theta. Dow Chemical is developing a new machine using an alpha-theta technique that will maintain both the position on the axis of rotation and the arm length, but vary both angles about the axis.

Frank Cooke has experience in both diamond turning and a diamond wheel. He reports experience

Table I. Optical Characterization of Diamond Turned Mirrors

Substrate	Plating	10.6 μm absorption	0.6 μm TIS[a] %	Roughness rms Å
OFHC Cu	None	0.0063[b]		
OFHC Cu	Cu	0.0098	0.17	
OFHC Cu	Ag	0.0071	0.073	20 Å
OFHC Cu	Au	0.0088[b]	0.082	
Brass	Ag	0.0067	0.27	
Molybdenum	Ag	0.0103	0.39	
Molybdenum	Au	0.0086[b]	0.060	

[a] Total integrated scatter (TIS) at 0.63 μm.

[b] $(1 - R)$, where R is measured on multiple bounce reflectometer.

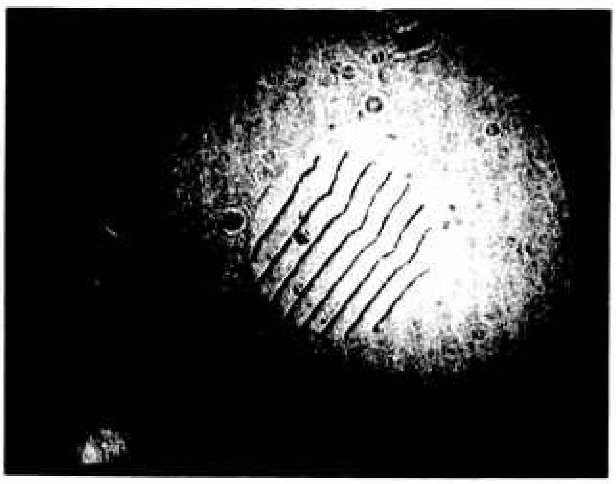

Fig. 1. This interferogram at 0.63 μm of a 3.8-cm diam diamond turned mirror demonstrates the importance of specifying slope error in machined optics. The localized ¼ fringe error is significantly different from the same error uniformly distributed over the mirror surface.

Table II. Summary of Organizations with Diamond Turning Capabilities

Organization	Numerical control available	Comments
Battelle Pacific Northwest, Richland, Washington	Yes	
Frank Cooke, N. Brookfield, Massachusetts	Yes	Experience with glass and salts
Dow Chemical, Rocky Flats, Golden, Colorado	Yes	Alpha-theta machine being developed
Lawrence Livermore Lab (LLL), Livermore, California	Yes	Machined an $f/0.25$ parabolic mirror[1]
Perkin-Elmer, Wilton, Connecticut	No	Automated industrial applications
Union Carbide, Y-12, Oak Ridge, Tennessee	Yes	

with machining glass and salts. Although diamond turning results in a good looking surface for NaCl, Cooke suspects that the salts will have exceptionally low laser damage threshold due to microcracks from the machining process. Although Cooke was not able to diamond turn glass successfully, he found that subsurface damage to the glass was much less when the tool was driven ultrasonically with 1 kW of power to follow an oval path at approximately 50 kHz. The subsurface damage was determined by etching the glass with HF.

Battelle Pacific Northwest Laboratories have been active in diamond turning for at least 3 years. They have worked in close contact with LLL in developing their capabilities.

Perkin-Elmer initiated studies of diamond turning (PSG is their nomenclature) in 1969.[18] Whereas Y-12 and LLL utilize flat belts to drive their motors, Perkin-Elmer uses a printed circuit motor to drive the work spindle. The machine was designed with production capabilities well in mind. After initial studies of diamond turning glass were discouraging, plastic was chosen as the optical material. Plastic lenses 5 cm in diameter were turned by Perkin-Elmer with a concave and convex surface (each of different radii) in 120 sec with a single surface deviation from spherical of 0.5 to one wave at 0.63 μm and a surface finish of 200-Å peak-to-valley roughness.

Machine Precision Grinding and Polishing

Frank Cooke of Cooke Optical and Werner Rambauske of Raytheon Space and Missile Division (Bedford, Mass.), have employed precision grinding techniques. Raytheon has concentrated on toric optics up to 60 cm in diameter. Raytheon also has fabricated conic optics that are hyperbolic in cross section. Their technique is quite different from diamond turning as demonstrated by their success with machining tungsten–carbide. Raytheon also uses a polishing technique. Some of their processes and applications are described in patent disclosures.[19]

Research and Development

One of the major problems in generating unusual shapes, such as the toroids, is the evaluation of the optical figure. Clever and innovative interferometry may help solve this problem. Continued development and refinement of machine accuracy will help reduce slope error. It may be possible to take advantage of the 250-Å repeatability of diamond turning machines by programming a numerically controlled machine to compensate for errors such as straightness of tool ways. Polishing (cloth, lap, or ion) of machined surfaces offers the possibility of improving surface roughness and optical figure. Gordon of Battelle Pacific Northwest Laboratories has had good success at Battelle Pacific Northwest Labs polishing diamond turned electroplated copper[20] with their process of a cloth lap and India ink polishing slurries.[21] Ion polishing results by Hoffman and his co-workers at Westinghouse are presented in this

issue.[22] Although ion polishing, in general, has failed to improve surfaces of polycrystalline metals,[16] I suspect that the cusplike nature of a diamond turned surface will lend itself to ion polishing techniques. Besides the continuing work at Westinghouse, diamond turned samples are being ion polished and studied in a joint program by Quella of Dow Chemical, Rocky Flats, and me. Since slope errors are sometimes localized, limited polishing may reap vast improvements.

An important aspect of diamond turning is that it may provide a technique to prepare a metal surface left in a better metallurgical state than polishing. There are two indications to verify this hypothesis. First, the highest reflectivity for bare copper has been from a diamond turned surface. Second, machined surfaces oxidize at a slower rate than polished surfaces. The oxidation of polished surfaces is often related to the disputed Beilby layer, which may be due to damage by the polishing technique.[23,24] Verification and implications of this hypothesis may be the subject of future surface physics and machining studies. Another important aspect of future machining research is the machinability of other materials such as ir windows, molybdenum, and glass.

In conclusion, machining of optics has developed to a technology level that is now competitive with superpolishing techniques for ir metal mirrors. Machining offers economy of fabrication time and flexibility in generated figure. An important step to future machining progress will be the evaluation and improvement of optical figure.

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